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ORIGINAL PAPER

Quantification by allometric equations of carbon sequestered by *Tectona grandis* in different agroforestry systems

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Abstract: Non destructive methods for quantification of carbon sequestration in tropical trees are inadequately developed. We described a standardized method for estimating carbon stock in teak (*Tectona grandis* Linn. F.). We developed linear allometric equations using girth at breast height (GBH), height and age to quantify above ground biomass (AGB). We used AGB to estimate carbon stock for teak trees of different age groups (1.5, 3.5, 7.5, 13.5, 18.5 and 23.5 years). The regression equation with GBH, $y = 3.174x - 21.27$, r^2=0.898 (p <0.01), was found precise and convenient due to the difficulty in determination of height and age in dense natural forests of teak. The equation was evaluated in teak agroforestry systems that included *Triticum aestivum* (wheat), *Cicer arietinum* (gram), *Withania somnifera* (ashwagandha), *Avena fatua* (wild oat) and *Hordeum vulgare* (barley) as agricultural crops established at Tropical Forest Research Institute, Jabalpur, M.P. (India). The annual carbon stock gain in teak in different agroforestry systems was in the order: teak-barley (60.47%) > teak-wheat (56.92%) > teak-wild oat (54.94%) > teak-gram (37.15%) > teak-ashwagandha (11.86%). The results from GBH-based regression equations provided satisfactory estimates of carbon stock in tropical trees.

Keywords: *Tectona grandis*; agroforestry system; allometric equation; carbon sequestration; above ground biomass

Introduction

Participating developing countries are required to report on the state of their forest resources under Reducing Emissions from Deforestation and Forest Degradation (REDD) and REDD plus to United Nation's Framework Convention on Climate Change (UNFCCC), which in turn is likely to assess their temporal and spatial carbon stocks (UNFCCC 2008). Several methods for estimating above ground biomass (AGB) stocks have been developed (Brown 1997; Clark et al. 2001; Phillips et al. 2002; Chave et al. 2004). However, these did not yield accurate estimates of carbon stocks in tropical forests due to lack of specific equations for computing AGB from tree measurements (Chave et al. 2005). Development of allometric regression equations to estimate AGB helped to fill this gap by working on the relationship of regular geometrical (i.e. frustum) form with girth at breast height (GBH), height, wood density and age of tree. Species-specific models were then needed to increase the accuracy of AGB estimates because of significant differences in architecture and wood density between trees of various species (Ketterings et al. 2001). Such models would improve the precision of estimates of carbon sequestration potential of various forest types or important tropical timber species. The information obtained would be helpful to devise conservation strategies for diverse forest types and economically important tropical trees exhibiting high carbon sequestration to combat the ill consequences of climate change and global warming.

Teak (*Tectona grandis* Linn. F.; Family: Verbenaceae) occurs in a natural zone of distribution confined to central and peninsular India below 24° N latitude (Troup 1921) and is the most important and highly valued commercial hardwood timber in the tropics (Hedegart 1975). Indian teak forests are found in the states of Madhya Pradesh, Maharashtra, Tamil Nadu, Karnataka, Kerala, Uttar Pradesh, Gujarat, Orissa and Rajasthan (Champion and Seth 1968). Our study was undertaken to develop allometric equations and test their application for estimating AGB and carbon stock of teak in various agroforestry systems.

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Materials and methods

Climate

The average monthly maximum and minimum temperatures (Tmax and Tmin), maximum and minimum relative humidity (Rhmax and Rhmin) and rainfall of the study area during 2009 are

listed in Fig. 1.

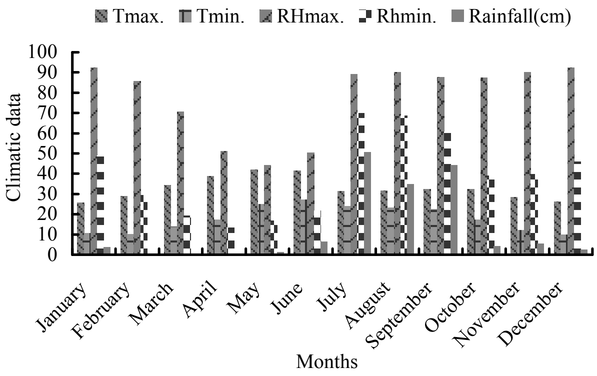

Fig. 1 Climatic data of study sites collected in 2009

Establishment of agroforestry systems

A 15 year-old teak plantation with spacing of 2 m × 2 m was used for establishing agroforestry systems in a simple randomized complete block design at the Tropical Forest Research Institute, Jabalpur, M.P. (India). Three blocks measuring 6 m × 12 m were selected for treatment and sampling in the teak plantation area. Each block was subdivided into six plots measuring 2 m × 6 m in which five agricultural crops, viz., *Triticum aestivum* (wheat), *Cicer arietinum* (gram), *Withania somnifera* (ashwagandha), *Avena fatua* (wild oat) and *Hordeum vulgare* (barley) and one control without the crop were randomly established. Thus, a total of 6 m × 6 m area was allocated to each crop and the control, and each treatment included 16 teak trees.

GBH of teak trees in all five agroforestry systems was measured by a measurement tape during 2009 and 2010. AGB values of the same teak trees was computed, employing a linear regression equation developed from standard GBH value of reference trees mentioned above (Fig. 2). The below ground biomass (BGB) of an experimental teak tree was calculated using using the formula BGB = 0.25×AGB as per guidelines of the Intergovernmental Panel on Climate Change. The carbon content was calculated as 0.5×total dry biomass (AGB+BGB) for each tree.

The regression equations and correlation coefficients obtained for different variables of reference teak trees were tested for statistical significance at α =0.05. Similarly, the computed teak AGB values in different agroforestry systems were also subjected to one way analysis of variance. If differences were found significant at α =0.01, CD (critical difference) values were computed at α = 0.05 or 0.01, i.e. $CD_{0.05}$ or $CD_{0.01}$ for comparison of mean values obtained from different treatments (agricultural crops and control).

Results

Development of allometric equations

Ten teak trees of six age groups (1.5, 3.5, 7.5, 13.5, 18.5 and 23.5 years) were selected from plantations of different ages and measured for GBH and height before being cut. Data were used for estimation of above ground biomass at Behrai Forest Range, Barghat Forest Division (22° 10' to 22° 57' N and 79°15' to 80°20' E) in Seoni district of Madhya Pradesh (India). Fresh weights of plant parts (leaves, branches and main stem) were determined followed by estimation of oven dry weights at 60°C−80°C (Table 1). The data were fit in various linear regression equations for above ground biomass developed against GBH, height and age groups (Figs. 2–4).

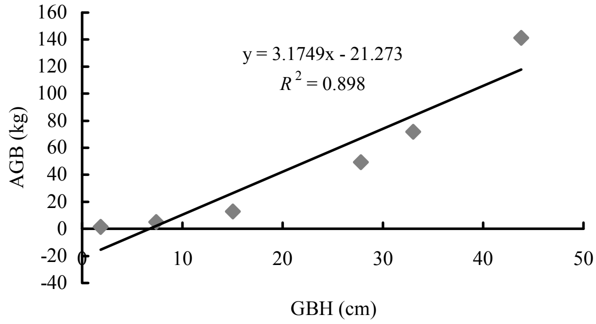

Fig. 2 Relationship between girth at breast height (GBH) and Above ground biomass (AGB) in *Tectona grandis.*

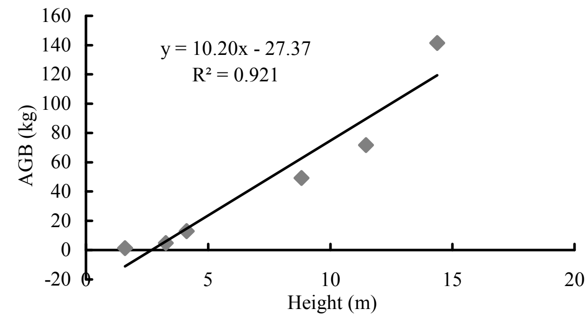

Fig. 3 Relationship between height and above ground biomass (AGB) in *Tectona grandis*

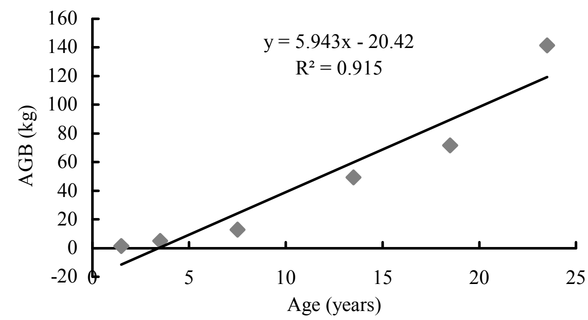

Fig. 4 Relationship between age and Above ground biomass (AGB) in *Tectona grandis*

GBH, height, and AGB of *T. grandis* trees increased with increasing tree age from 1.5 to 23.5 years (Table 1). GBH ranged from 1.86 to 43.80 cm, height from 1.60 to 14.38 m and AGB from 1.39 to 141.39 kg among the selected teak trees. Carbon sequestered per teak tree peaked at 68.04 kg in 2009 and 69.43 kg in 2010 in the teak-gram agroforestry system, This accounted for

170.10 t·ha^{-1} and 173.57 t·ha^{-1} during the two study years (for trees planted at 2 m × 2 m spacing, 2,500 tree·ha^{-1}).

Table 1. Growth and biomass in age series plantation of *Tectona grandis*.

S. No.	Age of the trees (years)	Average girth at breast height (cm)	Average height (m)	Aboveground biomass (kg)
1	1.5	1.86	1.60	1.39
2	3.5	7.40	3.27	4.94
3	7.5	15.04	4.13	12.90
4	13.5	27.80	8.83	49.22
5	18.5	33.00	11.46	71.78
6	23.5	43.80	14.38	141.39
SE(±)		0.4998	0.3310	0.4300
$CD_{0.05}$		1.0067	0.6669	0.8660
$CD_{0.01}$		1.3443	0.8902	1.1565

The greatest year-on-year increase (60.47%) in annual carbon stock was in the *T. grandis – Hordeum vulgare* agroforestry system, followed by *T. grandis – Triticum aestivum* (56.92%), *T. grandis – Avena fatua* (54.94%), and *T. grandis – Cicer arietinum* (37.15%). The minimum year-on-year increase was observed in *T. grandis – Withania somnifera* (11.86%). The year-on-year increase in teak as the pure stand was the tune of 2.53 (t/ha)·a^{-1}, i.e 1.54%. Kaul et al. (2010), while estimating year-on-year increase in carbon sequestration in different tropical trees, reported 2 (t/ha)·a^{-1} in teak (Fig. 5).

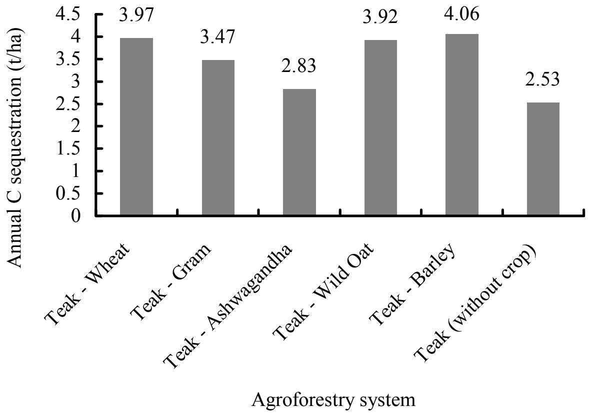

Fig. 5 Annual carbon sequestration rate of *Tectona grandis*

The linear regression equations and correlation coefficients for different variables of reference teak trees were significant (Figs. 2–4). The influence of five agricultural crops was found to be non-significant on AGB values of teak trees in both years (Table 2).

Table 2. Effect of agricultural crops on growth and carbon stock in *Tectona grandis* trees in various agroforestry systems during 2009 and 2010.

Agroforestry system	Characteristics of tree carbon component											
	Girth at breast height (cm)		Above ground biomass (kg)		Below ground biomass* (kg)		Total biomass (kg)		Total C/tree (kg)		Total C/ha with 2 m × 2 m spacing (t)	
	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010	2009	2010
Teak-Wheat	39.50	40.30	104.10	106.64	26.03	26.66	130.13	133.30	65.06	66.65	162.66	166.63
Teak-Gram	41.00	41.70	108.86	111.09	27.22	27.77	136.08	138.86	68.04	69.43	170.10	173.57
Teak-Ashwagandha	40.80	41.37	108.23	110.04	27.06	27.51	135.29	137.55	67.64	68.77	169.11	171.94
Teak-Wild Oat	39.65	40.44	104.58	107.09	26.14	26.77	130.72	133.86	65.36	66.93	163.40	167.32
Teak-Barley	39.15	39.97	102.99	105.59	25.75	26.40	128.74	131.99	64.37	65.99	160.93	164.99
Teak (without crop)	39.80	40.31	105.06	106.67	26.26	26.67	131.32	133.34	65.66	66.67	164.15	166.68
$LSD_{0.05}$	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.

* As per IPCC norms

Discussion

Forest timber trees locking AGB mostly in their main trunks differ with respect to shape, size and canopy dimensions. However, they exhibit striking similarity in their main trunks, which regularly taper from the base to the first branch. Branches at higher levels also maintain this pattern of growth. In geometry, the tapering cylinder is known as a frustum, Equ. 1 is a mathematical function of radius (maximum, *R*; minimum, *r*) or height (h).

$$V = \frac{\pi}{3(R^2 + Rr + r^2)} \tag{1}$$

GBH is a function of the trunk radius and is easy to measure. AGB is a multiplication of wood density by volume where wood density is assumed to be identical for various individuals of a timber tree species. This implies that AGB depends directly upon volume, thereby on GBH and height. This explains the strong correlation of AGB with GBH (Fig. 2) or height (Fig. 3) observed in our investigation. Similarly, we expect accumulation of similar average AGB at any particular age within the same tree species if environmental variables are constant, which corroborates the observed significant strong correlation between AGB and age (Fig. 4). However, accurate measurement of height or determination of age in a dense forest is difficult. In addition, the genetic diversity within forestry species limits the use of age as a reliable parameter, for trees of the same age can grow to different sizes. The literature cites GBH and height having been used for developing models for AGB computation (Brown et al. 1989). However, Williams and Schreuder (2000) advocated exclusion of height for such estima-

tions. The Akaike Information Criterion favours GBH based allometric models as the most suitable for *Dipterocarp* forests (Basuki et al. 2009).

The regular frustum structure of trees seems to be associated with resumption of secondary growth, i.e. attainment of woody nature. This accounts for negative values of AGB at early stage of teak growth to about 8 cm GBH (Fig. 2), 2−3 m height (Fig. 3) and 3−4 year age of teak trees (Fig. 4), and limits application of regression equations. The observation also strongly supports the assumption proposed above.

Five agricultural crops did not significantly influence carbon stock in teak trees. This is explained by the distribution of teak roots in soil strata deeper than those occupied by the roots of agricultural crops: There is little or no competition for mineral nutrients and water. Roots of agricultural crops penetrate the soil to depths of 30−45 cm while tree roots penetrate beyond 150−200 cm (Russel 1977).

Although carbon content of teak trees was not affected by agroforestry systems, significant decreases were recorded in economic yields of all five agroforestry crops, with maximum loss of 88% for gram and minimum loss of 64% for ashwagandha (Jain, unpublished). The teak tree over storey might have caused reduced yields in agroforestry crops by reducing sunlight intensity at the forest floor. This is why deciduous trees are incorporated into agroforestry systems for shedding leaves in winter to provide maximum irradiation to winter cereal crops for their optimal photosynthetic efficiency (Black and Ong 2000; Noordwijk and Lusiana 2000).

Carbon stock in *Tectona grandis* plantations and agroforestry systems was quantified during two consequent years, 2009 and 2010, and the difference in carbon stock showed the annual carbon sequestration rate of *Tectona grandis*. Annual carbon stock increased in this tree species when cultivated with short term agricultural crops, which could be due to ample supply of water and nutrients made available to agricultural crops and also due to regular soil working and increase in organic matter in the soil due to continuous addition of agricultural residues. _

In conclusion, our study provided GBH-based regression equations for estimation of carbon stocks in teak. We recorded no impact of agroforestry crops on carbon sequestration in teak trees.

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